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[File 2] INSPEC 1898-2006/Jan W2
[File 6] NTIS 1964-2006/Jan W4
[File 8] Ei Compendex(R) 1970-2006/Jan W4
[File 34] SciSearch(R) Cited Ref Sci 1990-2006/Jan W4
[File 434] SciSearch(R) Cited Ref Sci 1974-1989/Dec
[File 35] Dissertation Abs Online 1861-2006/Jan
[File 65] Inside Conferences 1993-2006/Jan W5
[File 94] JICST-EPlus 1985-2006/Nov W3
[File 99] Wilson Appl. Sci & Tech Abs 1983-2006/Apr
[File 144] Pascal 1973-2006/Jan W2
[File 23] CSA Technology Research Database 1963-2006/Jan
[File 103] Energy SciTec 1974-2006/Jan B1
[File 31] World Surface Coatings Abs 1976-2006/Jan
[File 95] TEME-Technology & Management 1989-2006/Jan W5
[File 68] Solid State & Superconductivity Abstracts 1966-2006/Jan
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[File 60] ANTE: Abstracts in New Tech & Engineer 1966-2006/Jan
[File 293] Engineered Materials Abstracts 1966-2006/Jan
[File 239] Mathsci 1940-2005/Feb
[File 256] TECINFOSOURCE 82-2005/DEC

Set	Items	Description
S1	2647516	S (WIRELESS OR WIRE()LESS OR REMOTE)(3N)(COMMUICAT?????? OR TELECOMMUNICAT?????) OR COMMUICAT??????? OR TELECOMMUNICAT?????
S2	20313	S (CHANNEL????? OR FREQUENC???????)(3N)(HOPP????? OR JUMP???? OR SKIP?????)
S3	330065	S (MITIGAT??????? OR ATTENUAT??????? OR SUPPRES???????? OR ALLEVIAT???????? OR DECREAS??????? OR LESS??????? OR MIMIMI?????? OR CANCEL??????? OR REDUC????? OR LOWER????)(3N)(NOIS????? OR INTERFER????????? OR DISTORT???????? OR TRANSIEN?????? OR CROSSTALK?????? OR CROSS()TALK????????)
S4	23008	S (NULL?????? OR ZERO?????? OR NIL)(3N)(PACKET?????? OR SIGNAL????? OR DATA OR INFORMATION OR INFO OR MESSAG???????)
S5	48963	S (IDENTIF??????? OR RECOGNI????????? OR VERIF????????? OR CONFIRM??????????)(3N)(NOIS????? OR INTERFER????????? OR DISTORT???????? OR TRANSIEN?????? OR CROSSTALK?????? OR CROSS()TALK????????)
S6	0	S S1 AND S2 AND S3 AND S4 AND S5
S7	14	S S1 AND S2 AND S4
S8	1	S S7 AND S3
S9	0	S S7 AND S5
S10	27	S S1 AND S2 AND S5
S11	0	S S10 AND S4
S12	5	S S10 AND S3
S13	1	S S2 AND S3 AND S4
S14	8	S S2 AND S3 AND S5
S15	6	RD (unique items)
S16	14	S S7 AND PY<=2002
S17	9	RD (unique items)
S18	3	S S12 AND PY<=2002
S19	3	RD (unique items)
S20	2754	S S4 AND (TRANSMI???????)
S21	189	S S20 AND S3
S22	0	S S21 AND S2
S23	115	S S21 AND S1
S24	0	S S23 AND BLUETOOTH
S25	0	S S23 AND (CHANNEL(2N)SCAN??????)
S26	0	S S23 AND S5
S27	1	S S23 AND CHANNEL(2W)CHANNEL
S28	89	S S23 AND PY<=2002
S29	65	RD (unique items)
S30	0	S S29 AND PERIODIC?????(2N)TRANSMI?????
S31	0	S S29 AND IEEE

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S32        0    S S29 AND ISM
S33        0    S S13 NOT S8
S34        6    S S15 NOT (S8 OR S13)
S35      837    S S3 AND S4
S36       21    S S35 AND S5
S37       14    RD  (unique items)
S38        8    S S37 AND PY<=2002
S39        8    S S17 NOT (S8 OR S13 OR S15)
S40        0    S S19 NOT (S8 OR S13 OR S15 OR S17)
S41        1    S S27 NOT (S8 OR S13 OR S15 OR S17 OR S19)
S42        8    S S38 NOT (S8 OR S13 OR S15 OR S17 OR S19 OR S27)
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[File 344] Chinese Patents Abs Jan 1985-2006/Jan
[File 347] JAPIO Nov 1976-2005/Sep(Updated 060103)
[File 350] Derwent WPIX 1963-2006/UD,UM &UP=200607
[File 371] French Patents 1961-2002/BOPI 200209

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S1    1722339    S (WIRELESS OR WIRE()LESS OR REMOTE)(3N)(COMMUICAT????? OR
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S2       3648    S (CHANNEL????? OR FREQUENC???????)(3N)(HOPP????? OR JUMP???? OR
SKIP?????)

S3     194971    S (MITIGAT??????? OR ATTENUAT??????? OR SUPPRES???????? OR
ALLEVIAT???????? OR DECREAS??????? OR LESS??????? OR MIMIMI?????? OR CANCEL??????? OR
REDUC????? OR LOWER????)(3N)(NOIS????? OR INTERFER????????? OR DISTORT???????? OR
TRANSIEN?????? OR CROSSTALK?????? OR CROSS()TALK????????)

S4      21555    S (NULL?????? OR ZERO?????? OR NIL)(3N)(PACKET?????? OR SIGNAL????? OR
DATA OR INFORMATION OR INFO OR MESSAG???????)

S5       3416    S (IDENTIF??????? OR RECOGNI?????????? OR VERIF????????? OR
CONFIRM??????????)(3N)(NOIS????? OR INTERFER????????? OR DISTORT???????? OR
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S6      79398    S MC=(W01-A03B OR W01-A06B5A OR W01-A06C4A OR W01-A06G2 OR W01-A07H2A
OR W02-K05A6)

S7      58249    S IC=(H04B-001/713 OR H04L-012/56 OR H04L-005/16)
S8          1    S S1 AND S2 AND S3 AND S4 AND S5 AND S6
S9          1    S S1 AND S2 AND S3 AND S4 AND S5
S10         9    S S1 AND S2 AND S4
S11         6    S S10 AND PY<=2002
S12         2    S S2 AND S3 AND S4
S13       142    S S1 AND S3 AND S4
S14         2    S S13 AND S5
S15         4    S S13 AND S6
S16         3    S S13 AND S7
S17      4498    S S4 AND TRANSMI???????
S18       183    S S17 AND S3
S19         4    S S18 AND (BLUETOOTH OR IEEE)
S20         8    S S18 AND S6
S21         4    S S18 AND S7
S22         0    S S9 NOT S8
S23         6    S S11 NOT (S8 OR S9)
S24         1    S S12 NOT (S8 OR S9 OR S11)
S25         3    S S15 NOT (S8 OR S9 OR S11 OR S12)
S26         1    S S16 NOT (S8 OR S9 OR S11 OR S12 OR S15)
S27         1    S S19 NOT (S8 OR S9 OR S11 OR S12 OR S15 OR S16)
S28         3    S S20 NOT (S8 OR S9 OR S11 OR S12 OR S15 OR S16 OR S19)
S29         0    S S21 NOT (S8 OR S9 OR S11 OR S12 OR S15 OR S16 OR S19 OR S20)
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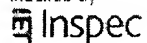
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		Results
#1	(((((channel hop*) or (frequenc* hop*)) and (interfer* or noise or distort*) and (null* or zero*))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2002)	21
#2	(((((channel hop*) or (frequenc* hop*)) and (interfer* or noise or distort*) and (null* or zero*))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2002)	21
#3	(((((channel hop*) or (frequenc* hop*)) and (interfer* or noise or distort*) and (null* or zero*))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2002)	21
#4	((((((null or zero)<near/2>(packet* or signal* or data*)) and (interfer* or nois* or distort*) and ((channel* hop*) or (frequenc* hop*)))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2001)	0
#5	((((((null or zero)<near/2>(packet* or signal* or data*)) and (interfer* or nois* or distort*))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2001)	173
#6	(((((null* packet*) or (null* signal*) or (null data)) and (interfer* or distort* or nois*) and ((frequenc* hop*) or (channel* hop*)))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2001)	0
#7	(((((null* packet*) or (null* signal*) or (null data)) and ((frequenc* hop*) or (channel* hop*)))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2001)	0
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#9	(((((null* packet*) or (null* signal*) or (null data)) and (interfer* or distort* or nois*))<in>metadata)) <and> (pyr >= 1950 <and> pyr <= 2001)	4
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Improving the performance of packet radio networks with adaptivearray antennas

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Dept. of Electr. Eng., Ohio State Univ., Columbus, OH;

Abstract
The authors propose a novel method to improve the performance of packet radio networks, namely, using adaptive array antennas on the packet radio units instead of omnidirectional antennas. An adaptive array can acquire a packet arriving from one direction and then null packets from other directions to prevent them from interfering with the acquired packet. By protecting the acquired packet, an adaptive array allows one packet to be received, even when interfering packets are present. To investigate the effect of an adaptive array on packet radio network performance, the authors consider a simple two-hop packet radio network with an adaptive array at the station. These preliminary results show that an adaptive array can greatly increase the throughput

Index Terms
Inspec

> ### Controlled Indexing
> antenna phased arrays   antenna theory   frequency agility   packet switching   radio networks
>
> ### Non-controlled Indexing
> adaptive array antennas   null packets   packet radio networks   performance improvement   throughput
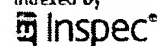> two-hop packet radio network

Author Keywords
Not Available

References

No references available on IEEE Xplore.

Citing Documents

No citing documents available on IEEExplore.

IMPROVING THE PERFORMANCE OF PACKET RADIO NETWORKS WITH ADAPTIVE ARRAY ANTENNAS

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Department of Electrical Engineering
The Ohio State University
205 Dreeese Laboratory
Columbus, OH 43210

Abstract

We propose a novel method to improve the performance of packet radio networks: use adaptive array antennas on the packet radio units, instead of omnidirectional antennas. An adaptive array can acquire a packet arriving from one direction and then null packets from other directions, to prevent them from interfering with the acquired packet. By protecting the acquired packet, an adaptive array allows one packet to be received, even when interfering packets are present. To investigate the effect of an adaptive array on packet-radio-network performance, we consider a simple two-hop packet radio network with an adaptive array at the station. These preliminary results show that an adaptive array can greatly increase the throughput compared to a conventional omnidirectional antenna.

I.   Introduction

We propose a novel method to improve the performance of multihop Packet Radio Networks (PRN's) [1]: use adaptive array antennas [2] on the packet radio units, instead of omnidirectional antennas. An adaptive array takes advantage of a previously unused parameter in a packet radio system: packet arrival angle. An adaptive array can acquire a packet arriving from one direction and then null packets from other directions, preventing them from interfering with the acquired packet. By protecting an acquired packet in this way, an adaptive array allows one packet to be received, even when interfering packets are present. Analysis of a simple PRN shows that this capability can greatly increase the throughput-delay performance compared to a conventional omnidirectional antenna. These results also indicate that even a relatively simple adaptive array, with only a few array elements, can dramatically improve performance. The adaptive array is an attractive alternative to other performance enhancement methods, since it improves

performance without the need for additional bandwidth or the introduction of complex control schemes. The design of a random-access adaptive array system was first described by Compton and Garber et. al. in [3], where a satellite channel was considered.

To investigate the the effect of an adaptive array on PRN performance, we consider a simple two-hop PRN with an adaptive array at the station. We analyze this network by extending the PFS-control technique developed in [4,5]. Because the network has a PFS, when operating under PFS-control, we are able to find the equilibrium probabilities in closed form, and derive simple, exact expressions for the expected throughput and the expected delay.

II.   Operation of the Adaptive Array Antenna

For proper operation of the adaptive array, it must first distinguish between desired and interfering packets, and then acquire the desired packet while nulling the interfering packets.

A new technique was developed in [3] to allow the application of adaptive arrays to satellite networks using the slotted-ALOHA [1] protocol. In this technique, packets begin with a two-part preamble. The first part of the preamble is chosen so that its autocorrelation function has a narrow peak and a high peak-to-sidelobe ratio. This narrow peak is used as a timing spike to trigger the packet acquisition process.

The second part of the preamble is used by the feedback loop of the adaptive array to null the interfering packets. The time constant of the feedback loop is designed to form a beam pattern by the end of the second part of the preamble. The beam has a maximum pointing in the direction of the desired packet and nulls pointing in the direction of interfering packets. The body of the desired packet can then be successfully received by the station. The adaptive array resets its pattern at the end of each slot, so that it is ready to acquire and null new packets in the next time slot.

When more than one packet is transmitted to the station in the same time slot, the packet which arrives first will be acquired by the adaptive array and

6.6.1.

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the others will be nulled. This *acquisition* probability will be denoted by p_{acq}. To guarantee fairness, terminals randomize their packet transmission times over a small time interval at the beginning of each time slot.

The *nulling* capability of an adaptive array, denoted by a, is determined by the number of array elements it has. In general, an L–element adaptive array can null $L - 2$ interfering packets. When the nulling capability is exceeded, the desired packet is lost. Another limitation of the adaptive array is its angular resolution. When the direction of interfering packet(s) is too close to that of the desired packet, the adaptive array may not be able to distinguish one packet from the other and all the packets may be lost. The angular resolution improves as the number of array elements increases. In this paper, we assume that the adaptive array has perfect angular resolution, i.e., it will always acquire the first packet no matter how close the interfering packet transmitters are to the desired packet transmitter. It is not difficult to modify our analysis to include the effects of limited angular resolution on network performance.

III. Two-Hop Slotted-ALOHA Packet Radio Network

A. Model

We consider a PRN consisting of two groups of terminals, A and B, which are out of transmission range of each other, but in range of a common station. The station is equipped with an adaptive array. The station and all the terminals use the same slotted-ALOHA channel which has time slots one unit long. The channel is assumed to be error free; if a terminal hears only one packet in a time slot, that packet is received correctly. If two or more packets are transmitted in the same time slot, neither is received correctly by a terminal and both must be retransmitted. We assume that the station and terminals know immediately whether their single-hop transmissions are successful or not.

Two *local* terminals, one from each group, communicate through the station: terminal A_L in group A and terminal B_L in group B. Terminal A_L has message packets for terminal B_L which must be relayed by the station, since A_L and B_L are out of range of each other. Terminal B_L returns one acknowledgment, which must also be relayed by the station, for each message packet received from A_L. The acknowledgment packets are the same length as message packets and are transmitted on the same channel. The remaining terminals in each group, called *background* terminals, only have packets for terminals that are in their group; they do not forward packets through the station. The background terminals are heard by either terminal A_L or terminal B_L, respectively, and by the station, thus interfering with the flow of packets

between terminal A_L and terminal B_L.

We assume that terminal A_L operates under a sliding-window flow control scheme [1]. This means that terminal A_L is not allowed to have more than N unacknowledged packets outstanding. When there are N unacknowledged packets, it stops transmitting until an acknowledgment is received. Thus, N is terminal A_L's *window size*. We also make the worst-case assumption that terminal A_L always has packets to transmit and only stops transmitting when it has N unacknowledged packets.

B. Discrete-Time Markov Chain

The queueing model is shown in Figure 1. The transmission probabilities for each of the queues are shown, along with the path of the message and acknowledgment packets. We define the queue lengths as: n_{A_L}, the number of message packets at terminal A_L; n_{B_L}, the number of acknowledgment packets at terminal B_L; n_{A_S}, the number of acknowledgment packets at the station for transmission to terminal A_L; and n_{B_S}, the number of message packets at the station for transmission to terminal B_L.

The channel state at time slot t is completely defined by $CS_t = (n_{A_L}, n_{A_S}, n_{B_S})$. We do not need to include n_{B_L} in the channel state because $n_{A_L} + n_{A_S} + n_{B_L} + n_{B_S} = N$.

The probability that terminal A_L [B_L] transmits in the next time slot when $CS_t = (j, k, l)$ is defined as $p^{A_L}_{j,k,l}$ [$p^{B_L}_{j,k,l}$]. Each group-A [group-B] background terminal transmits in a time slot with constant probability p^A [p^B]. There are K_A group-A background terminals and K_B group-B background terminals.

The station decides whether to transmit a message packet or an acknowledgment packet using the routing probability $r_{j,k,l}$. Message packets are chosen from the B_S queue (see Figure 1) with probability $(1-r_{j,k,l})$ and acknowledgments are chosen from the A_S queue with probability $r_{j,k,l}$. The station transmits the chosen packet in the next time slot with probability $p^S_{j,k,l}$. If the station only has packets in one of its queues, it chooses a packet for transmission from that queue with probability equal to 1. It follows from the above definitions that CS_t is a Markov Chain with a finite number of states, $\binom{N+3}{3}$.

C. State Transition Diagram and Consistency Graph

To generate the state transition diagram, transition probabilities, consistency graph, and global balance equations for the N-packet network, we begin with the 1-packet network ($N = 1$). For this reason, we present the expressions for the 1-packet network in terms of arbitrary j, k, l and N, with the understanding that for the 1-packet network $j = k = l = 0$ and $N = 1$.

The state transition probabilities for arbitrary j, k, and l are given below. We use the notation $Q_1 \rightarrow Q_2$ to indicate a successful transmission from the Q_1

6.6.2.

queue to the Q_2 queue. We use the notation $\bar{p}$ for $(1-p)$.

$$A_L \to B_S \; : \; \mathrm{P}(j,k,l+1|j+1,k,l) =$$
$$p^{A_L}_{j+1,k,l}\bar{p}^{S}_{j+1,k,l}I_{B_L}(j+1,k,l)$$

$$A_S \to A_L \; : \; \mathrm{P}(j+1,k,l|j,k+1,l) =$$
$$r_{j,k+1,l}\,p^{S}_{j,k+1,l}\bar{p}^{A_L}_{j,k+1,l}(\bar{p}^{A})^{K_A}$$

$$B_L \to A_S : \mathrm{P}(j,k+1,l|j,k,l) = p^{B_L}_{j,k,l}\bar{p}^{S}_{j,k,l}I_{A_L}(j,k,l)$$

$$B_S \to B_L : \mathrm{P}(j,k,l|j,k,l+1) = \bar{r}_{j,k,l+1}p^{S}_{j,k,l+1}\bar{p}^{B_L}_{j,k,l+1}(\bar{p}^{B})^{K_B}$$

where $0 \le j+k+l \le N-1$ and

$$I_{A_L}(j,k,l) = \left[1 - p^{A_L}_{j,k,l}(1-p_{acq})\right]\sum_{s=0}^{a-1}D(s) + \bar{p}^{A_L}_{j,k,l}D(a)$$

$$I_{B_L}(j,k,l) = \left[1 - p^{B_L}_{j,k,l}(1-p_{acq})\right]\sum_{s=0}^{a-1}D(s) + \bar{p}^{B_L}_{j,k,l}D(a)$$

$D(s)$ is the probability that s of the background terminals transmit. Since the station has an adaptive array, a transmission from either local terminal to the station is successful only if the total number of transmissions from the background terminals and the other local terminal is less than or equal to a. Thus, $I_{A_L}(j,k,l)$ [$I_{B_L}(j,k,l)$] is the probability that less than or equal to a of the background terminals and terminal A_L [B_L] transmit and that the packet from terminal B_L [A_L] is acquired by the adaptive array, when $CS_t = (j,k,l)$.

Using the state transition diagram, we find the following set of global balance equations [1]

$$\pi_{j,k+1,l} = a_{j,k,l}\pi_{j,k,l}\,, \quad \pi_{j+1,k,l} = b_{j,k,l}\pi_{j,k+1,l}$$

$$\pi_{j,k,l+1} = c_{j,k,l}\pi_{j+1,k,l}\,, \quad \pi_{j,k,l} = d_{j,k,l}\pi_{j,k,l+1}$$

where $a_{j,k,l} = \frac{\mathrm{P}(j,k+1,l|j,k,l)}{\mathrm{P}(j+1,k,l|j,k+1,l)}$, $b_{j,k,l} = \frac{\mathrm{P}(j+1,k,l|j,k+1,l)}{\mathrm{P}(j,k,l+1|j+1,k,l)}$, $c_{j,k,l} = \frac{\mathrm{P}(j,k,l+1|j+1,k,l)}{\mathrm{P}(j,k,l|j,k,l+1)}$, and $d_{j,k,l} = \frac{\mathrm{P}(j,k,l|j,k,l+1)}{\mathrm{P}(j,k+1,l|j,k,l)}$. The $\pi_{j,k,l}$'s are the equilibrium probabilities for the Markov Chain CS_t.

The *consistency graph* [6] shows the relationship between the equilibrium probabilities graphically. The weights along the arcs of the consistency graph relate the equilibrium probabilities at the nodes, and they are found directly from the balance equations.

To construct the state transition diagram for the Markov Chain CS_t for arbitrary N, we combine 1-packet state transition diagrams or cells This process is described more completely in [4,5]. Similarly, the N-packet consistency graph is constructed by pasting together 1-packet consistency graphs.

IV. PFS-Control

The consistency graph method [6] will be used to find conditions on the transmission and routing probabilities, $p^{S}_{j,k,l}$ and $r_{j,k,l}$, which guarantee that the set of partial balance equations is consistent. These conditions will define the PFS-control. As proven in [6], the system of partial balance equations is consistent if and only if the product of the arc weights around any closed path of the consistency graph is equal to one.

There are three basic consistency equations, called AB, AC, and $ABCD$. Each consistency equation is a function of its subscripts (j, k, l), and these subscripts range over a set of nonnegative integers depending on N. The consistency equations are listed below.

$$AB : \; a_{j,k,l}\,\frac{1}{a_{j,k+1,l}}\,b_{j,k,l}\,\frac{1}{b_{j,k+1,l}} = 1 \qquad (1)$$

$$AC : \; a_{j+1,k,l}\,\frac{1}{a_{j,k,l+1}}\,c_{j,k+1,l}\,\frac{1}{c_{j,k,l}} = 1 \qquad (2)$$

$$ABCD : \; a_{j,0,l+1}\,b_{j,0,l+1}\,c_{j,0,l}\,d_{j+1,0,l} = 1 \qquad (3)$$

where $0 \le j+k+l \le N-2$. To find the PFS-control, the consistency equations are solved for the station's transmission and routing probabilities, $p^{S}_{j,k,l}$ and $r_{j,k,l}$.

Before solving the consistency equations, we assume that local terminals A_L and B_L only have local knowledge of the network state. They only know two quantities: the number of packets they have for transmission, and N, which is the number of packets in terminal A_L's window. Thus, we have

$$p^{A_L}_{j,k,l} = \begin{cases} p^{A_L}_j, & j > 0 \\ p^{A_L}_0, & j = 0 \end{cases}, \quad p^{B_L}_{j,k,l} = \begin{cases} p^{B_L}_{N-j-k-l}, & j+k+l < N \\ p^{B_L}_0, & j+k+l = N \end{cases}$$

This also means that $I_{A_L}(j,k,l) = I_{A_L}(j)$ and $I_{B_L}(j,k,l) = I_{B_L}(m)$, where $m = N - j - k - l$.

The key to the solution of the consistency equations for arbitrary N is that the functional form of the solution depends *only* on the pattern of empty and non-empty queues. For each pattern of empty and non-empty queues, we get a particular function for the station's transmission and routing probabilities, $p^{S}_{j,k,l}$, and $r_{j,k,l}$. We use the notation $(n_{A_L}, n_{A_S}, n_{B_S}, n_{B_L})$ to indicate the number of packets in each queue. If we only want to indicate whether the queues are empty or non-empty, we use o's and x's, respectively, instead of numbers. Using the notation described above, the PFS-control is given in the following

Theorem 1: The transmission and routing probabilities, $r_{j,k,l}$ and $p^{S}_{j,k,l}$, given below satisfy the consistency equations (Equations (1)-(3)) for any N. This is the PFS-control. If the station uses these transmis-

6.6.3.

sion and routing probabilities, the network will have a PFS for the equilibrium probabilities.

$$(o,o,x,x)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{B_L}(m)\overline{p}_0^{B_L}}{q_{k+l}^S I_{B_L}(m)\overline{p}_0^{B_L} + I_{B_L}(0)\overline{p}_m^{B_L}}$$

$$(x,x,o,o)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{A_L}(j)\overline{p}_0^{A_L}}{q_{k+l}^S I_{A_L}(j)\overline{p}_0^{A_L} + I_{A_L}(0)\overline{p}_j^{A_L}}$$

$$(x,o,x,x)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{A_L}(j)I_{B_L}(m)\overline{p}_0^{B_L}}{q_{k+l}^S I_{A_L}(j)I_{B_L}(m)\overline{p}_0^{B_L} + I_{A_L}(0)I_{B_L}(0)\overline{p}_m^{B_L}}$$

$$(x,o,x,o)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{A_L}(j)}{q_{k+l}^S I_{A_L}(j) + I_{A_L}(0)}$$

$$(x,x,o,x)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{A_L}(j)I_{B_L}(m)\overline{p}_0^{A_L}}{q_{k+l}^S I_{A_L}(j)I_{B_L}(m)\overline{p}_0^{A_L} + I_{A_L}(0)I_{B_L}(0)\overline{p}_j^{A_L}}$$

$$(o,x,o,x)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{B_L}(m)}{q_{k+l}^S I_{B_L}(m) + I_{B_L}(0)}$$

$$(x,x,x,x)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{A_L}(j)I_{B_L}(m)\left[\overline{p}_0^{A_L}\overline{p}_m^{B_L} + \overline{p}_j^{A_L}\overline{p}_0^{B_L}\right]}{\left\{ q_{k+l}^S I_{A_L}(j)I_{B_L}(m)\left[\overline{p}_0^{A_L}\overline{p}_m^{B_L} + \overline{p}_j^{A_L}\overline{p}_0^{B_L}\right] \right. }$$
$$\left. + I_{A_L}(0)I_{B_L}(0)\overline{p}_j^{A_L}\overline{p}_m^{B_L} \right\}$$

$$(o,x,x,x)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{B_L}(m)\left[\overline{p}_0^{B_L} + \overline{p}_m^{B_L}\right]}{q_{k+l}^S I_{B_L}(m)\left[\overline{p}_0^{B_L} + \overline{p}_m^{B_L}\right] + I_{B_L}(0)\overline{p}_m^{B_L}}$$

$$(x,x,x,o)\, p_{j,k,l}^S = \frac{q_{k+l}^S I_{A_L}(j)\left[\overline{p}_0^{A_L} + \overline{p}_j^{A_L}\right]}{q_{k+l}^S I_{A_L}(j)\left[\overline{p}_0^{A_L} + \overline{p}_j^{A_L}\right] + I_{A_L}(0)\overline{p}_j^{A_L}}$$

$$(o,x,o,o),(o,o,x,o),(o,x,x,o)\ 0 < p_{j,k,l}^S < 1$$

where $m = N - j - k - l$ is the number of packets in terminal B_L's queue and where $0 < q_{k+l}^S < 1$; $0 < p_i^{A_L}, p_i^{B_L} < 1$, for $i > 0$; and $0 \le p_0^{A_L}, p_0^{B_L} < 1$. If either of the station's queues is empty, we choose packets from the non-empty queue with probability equal to 1, so $r_{j,k,l} = 1$ when $l = 0$ and $r_{j,k,l} = 0$ when $k = 0$. The routing probabilities when the station has packets in both queues are given by

$$(x,x,x,x)\, r_{j,k,l} = \frac{\overline{p}_0^{A_L}\overline{p}_m^{B_L}}{\overline{p}_0^{A_L}\overline{p}_m^{B_L} + \overline{p}_0^{B_L}\overline{p}_j^{A_L}}$$

$$(x,x,x,o)\, r_{j,k,l} = \frac{\overline{p}_0^{A_L}}{\overline{p}_0^{A_L} + \overline{p}_j^{A_L}}$$

$$(o,x,x,x)\, r_{j,k,l} = \frac{\overline{p}_m^{B_L}}{\overline{p}_0^{B_L} + \overline{p}_m^{B_L}},\quad (o,x,x,o)\, r_{j,k,l} = \frac{1}{2}$$

Proof: For a proof, see [5]. ∎

V. Equilibrium Probabilities and Throughput-Delay Performance

A. Equilibrium Probabilities

The equilibrium probabilities are the solution to the equation $\pi Q = \pi$ where Q is the state transition matrix for the irreducible Markov Chain CS_t and π is the vector of equilibrium probabilities [1]. If the partial balance equations are consistent, we can use the consistency graph to write the equilibrium probability at each node of the state transition diagram in terms of a reference node. This leads to the following

Theorem 2: When the two-hop PRN is under PFS-control, the equilibrium probabilities for the Markov Chain CS_t are given by

$$\pi_{j,k,l} = \left[\prod_{u=0}^{j-1} b_{u,j+k-u-1,0}\right]\left[\prod_{v=0}^{j+k-1} a_{0,v,0}\right]\left[\prod_{w=0}^{l-1}\frac{1}{d_{j,k,w}}\right]\pi_{0,0,0},$$

where $0 \le j + k + l \le N$. The normalization constant $\pi_{0,0,0}$ is chosen so that the equilibrium probabilities sum to 1. ∎

B. Throughput-Delay Performance

Because terminal A_L requires an acknowledgment for each packet and stops transmitting if there are N unacknowledged packets, the (steady state) throughput along all four hops must be the same.

The throughput on each hop is the probability that a transmission along that hop is successful, since the time slots are one unit long. So we have the following throughput expressions

$$T_{A_L} = \sum_{j=1}^{N}\sum_{k=0}^{N-j}\sum_{l=0}^{N-j-k} P(j-1,k,l+1|j,k,l)\,\pi_{j,k,l}$$

$$T_A = \binom{K_A}{1} p^A (\overline{p}^A)^{K_A-1} \sum_{j=0}^{N}\sum_{k=0}^{N-j}\sum_{l=0}^{N-j-k} \overline{p}_{j,k,l}^{A_L}\,\overline{p}_{j,k,l}^{S}\,\pi_{j,k,l}$$

where T_{A_L} is the throughput from terminal A_L to the station and T_A it the throughput of the group-A background terminals. The other throughput expressions are similar. Little's result gives the expected delay along each hop.

C. Sample System

We allow at most 6 unacknowledged packets ($N = 6$). The background populations are identical. All background terminals use the same transmission probability and there are 9 background terminals in each group ($p^A = p^B = 0.1$, $K_A = K_B = 9$). The local terminals A_L and B_L are also identical and use constant transmission probability p^L ($p_j^{A_L} = p_j^{B_L} = p^L$). The station uses a constant transmission parameter $q_{k+l}^S = q^S$. We assume that the acquisition probability, p_{acq}, is equal to 1/2.

6.6.4.

To examine the performance with adaptive arrays, we varied the network parameters to find the maximum possible packet throughput from terminal A_L to terminal B_L, and then plotted this maximum throughput versus the number of adaptive array nulls in Figure 2. This figure shows that the packet throughput from terminal A_L to terminal B_L, which is relayed by the station, almost doubles (from 0.065 packets per slot to 0.12 packets per slot) when we have a 4-null adaptive array at the station. (If these throughput values seem small, keep in mind that they only include traffic relayed through the station. The background terminals also contribute to the total throughput.) In Figure 3, we plot the expected delay for packets traveling from terminal A_L to terminal B_L as a function of the number of adaptive-array nulls. This shows that the expected delay drops dramatically as nulling capability is added to the station. Also note that only a small number of array elements are needed. For example, if the adaptive array has 2 nulls (4 array elements) the throughput and delay are both within a few percent of their optimum values.

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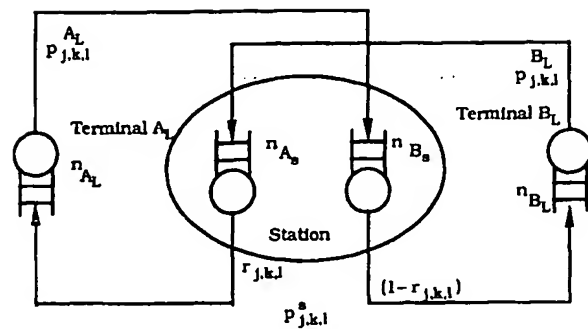
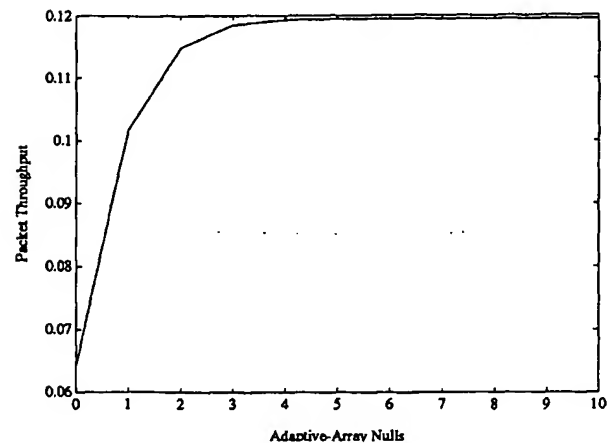Figure 1: Queueing model for the two-hop PRN.

Figure 2: Packet throughput (in packets per slot) from terminal A_L to terminal B_L versus the number of adaptive-array nulls.
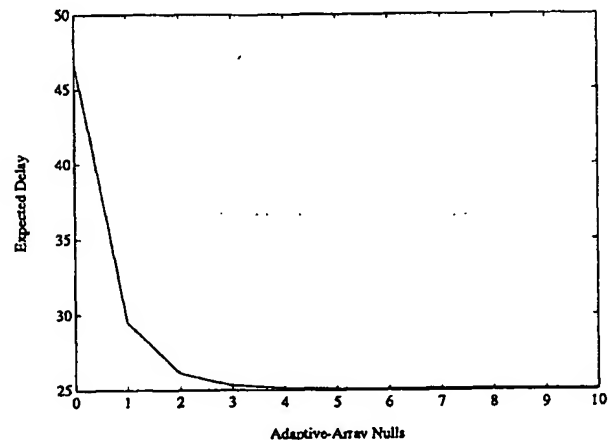

Figure 3: Expected delay (in slots) for packets traveling from terminal A_L to terminal B_L versus the number of adaptive-array nulls.

6.6.5.